Arctic Coastal Mesh Refinement in a Global Earth System Model

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Summary

The Arctic has undergone perhaps the largest physical transition of any region on Earth over the past two decades as a result of increasing global greenhouse gas concentrations. Climate change has left high northern coasts susceptible to sea level rise, wave action and storm surge, where landfast and thick perennial sea ice once modulated coastal exposure. We are learning to incorporate mesoscale coastal physics and biogeochemistry into Earth System Models to enhance understanding of the changing state of the ocean and sea ice in relatively shallow regions (<500m) and at eddy-permitting scales. Here, we isolate one aspect of our development – that of regional mesh refinement in a fully coupled global Earth system model. Using Version 2 of the Energy Exascale Earth System Model (E3SMv2), we demonstrate the impact of mesh refinement in the proximity of Arctic coasts, and across the Arctic system. We present analysis of the sea ice state in a simple controlled study that isolates the combined impacts of regionally-refined ocean-ice and atmosphere-land components (∼14km and ∼25km resolution respectively) as compared to standard coupled model resolution (∼30 and ∼110km resolution) in 500-year preindustrial simulations (Figures 1 & 2). Against a background of eddy versus non-eddy resolving ocean physics, and improved representation of Arctic storms accommodated by increased resolution, all other aspects of E3SM remain the same including column physics in each model, except for numerical changes necessitated by enhanced resolution. A robust Arctic signal emerges from these long simulations with a dramatic increase in sea ice thickness with higher resolution; no comparable change occurs for Antarctic sea ice, where resolution is nominally the same between the two simulations (Figures 3 & 4).

Arctic Mesh Refinement in E3SM Version 2

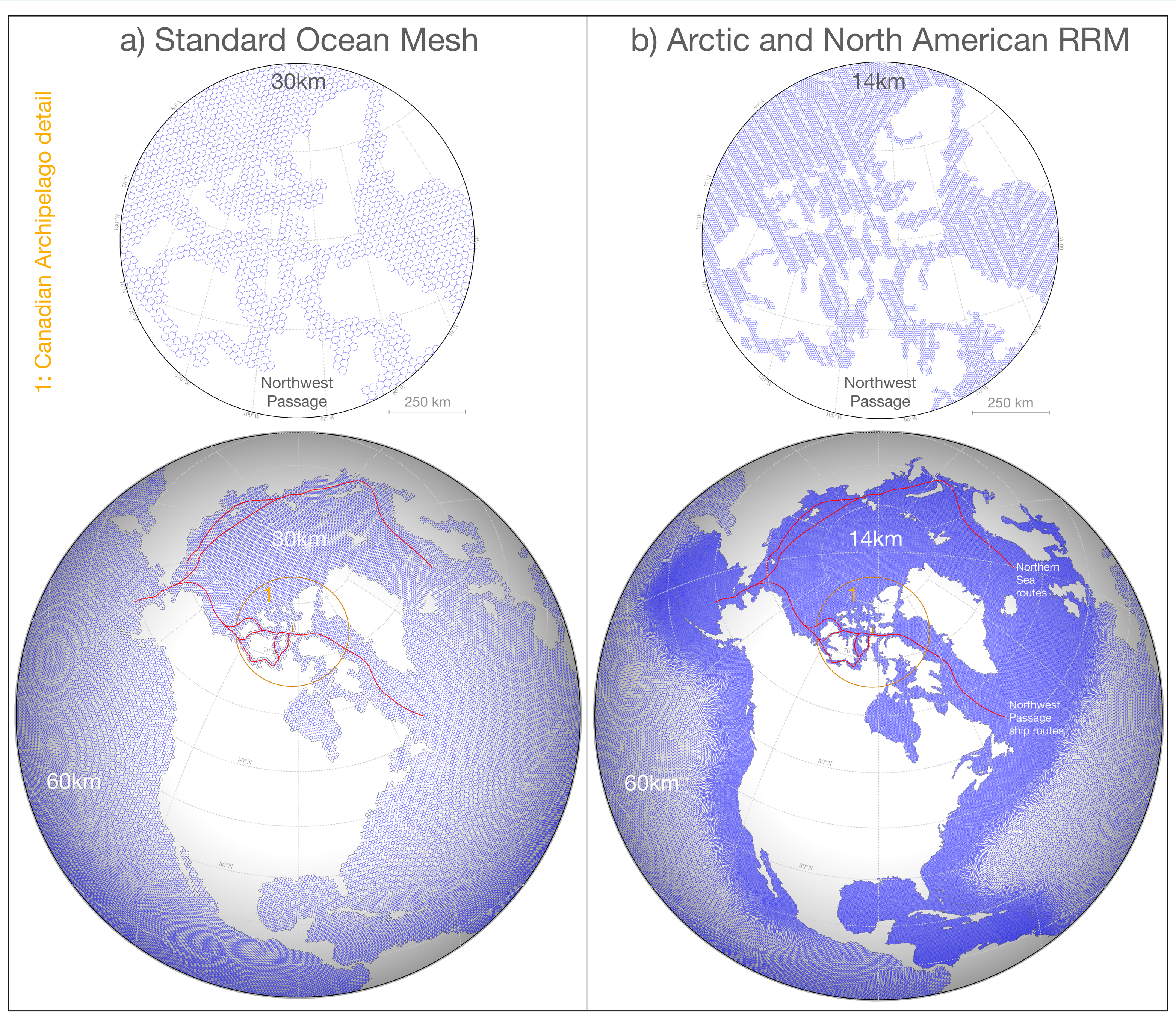


Figure 1 (above): Comparison of (a) the standard E3SMv2 ocean mesh with (b) the Arctic and North American regionally-refined ocean mesh (RRM). Top row provides scaled close-ups of the Canadian Archipelago illustrating the degree of refinement relative to the standard mesh. 14, 30 and 60 km annotations indicate the resolution of the mesh at the given locations. All configurations resolve Arctic coastal shipping routes (red), but the RRM ensures a realistic channel width.

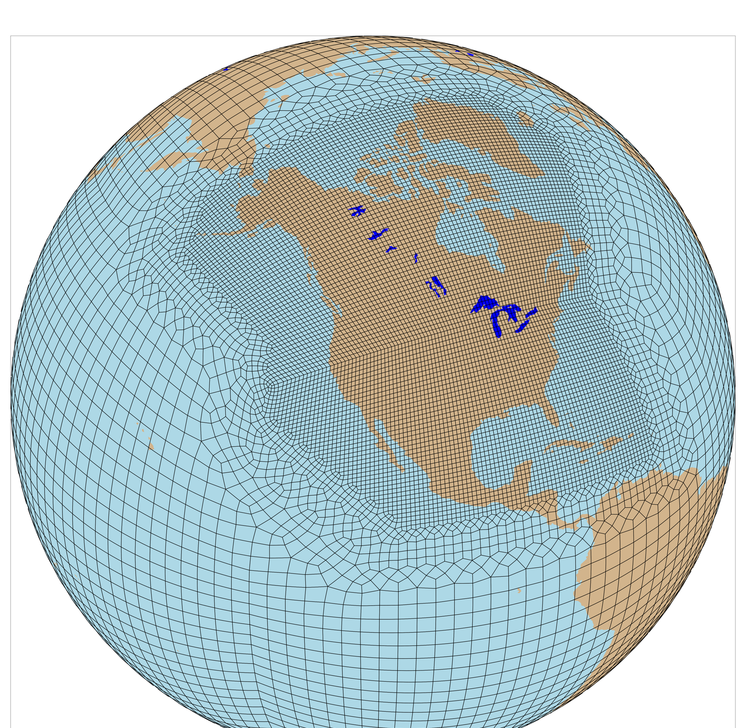


Figure 2 (right): The North American regionally-refined atmospheric mesh includes refinement to 25km over the American Arctic.

Impact of Regional Refinement on Sea Ice Mass & Bias

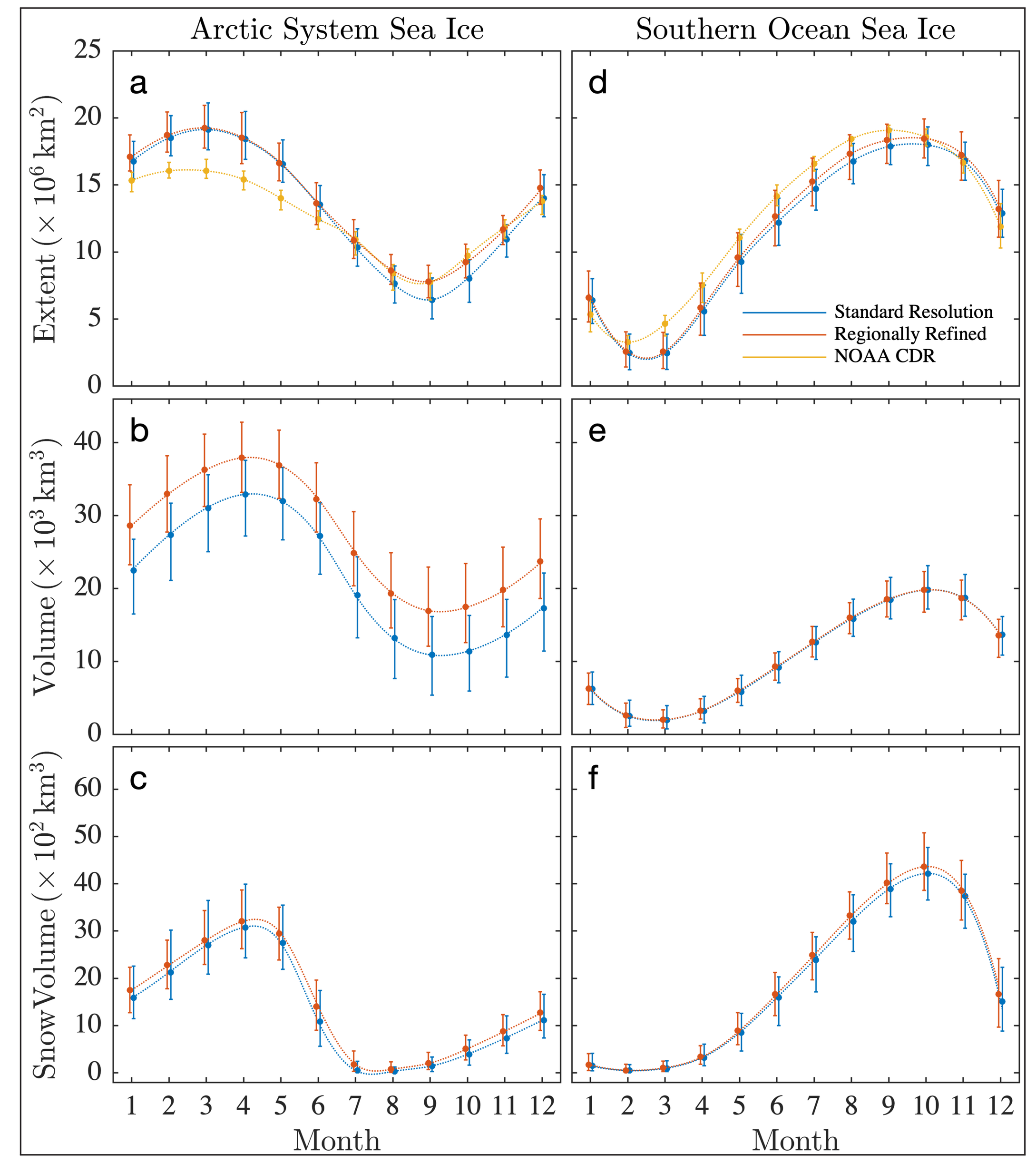
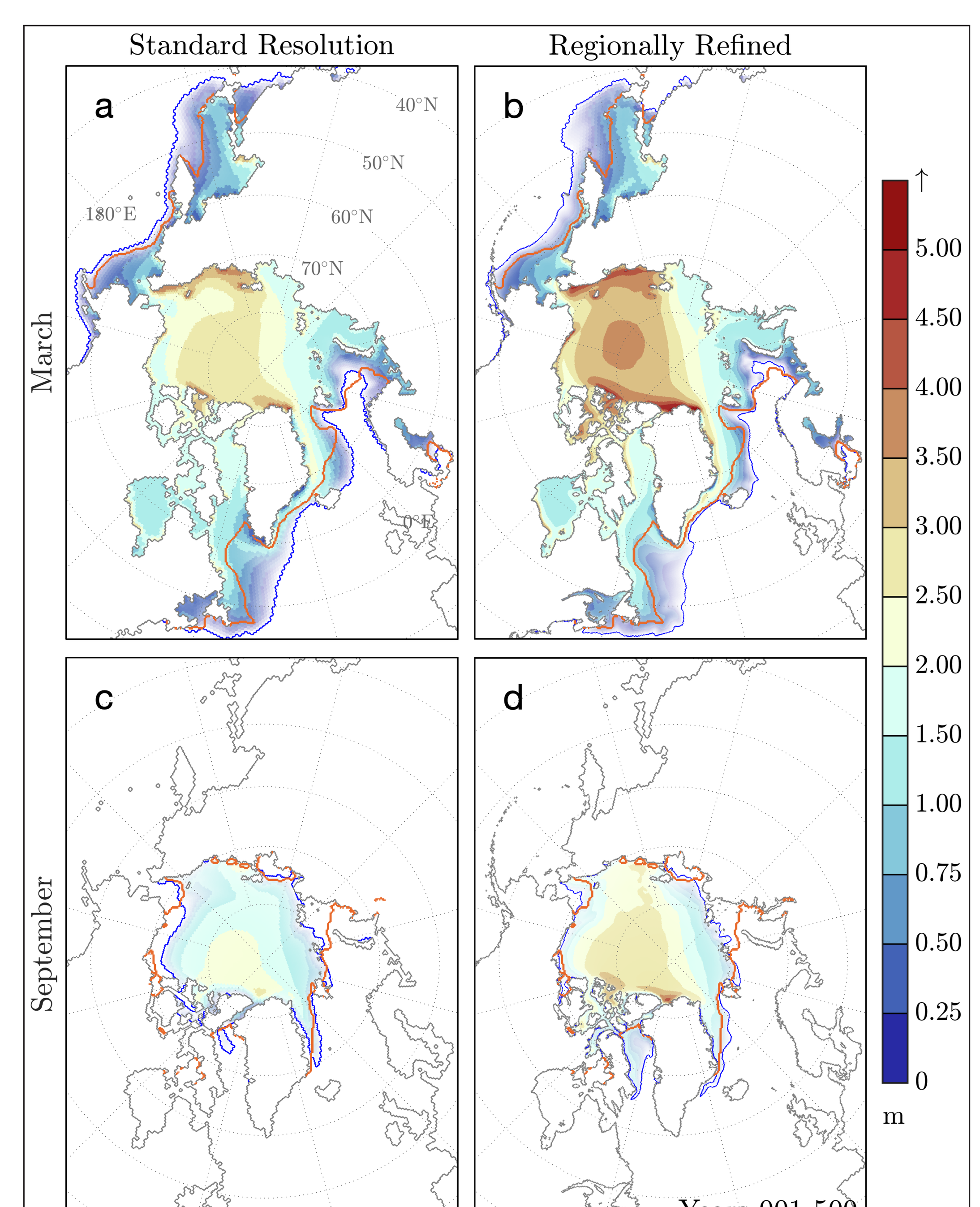


Figure 3 (left): Arctic regional refinement results in an average 5000 to 6400 km^3 greater simulated ice volume in the Northern Hemisphere than is produced at standard resolution, a ∼16-57% increase over the annual cycle of the 500-year preindustrial simulations summarized here. The median, maximum, and minimum sea ice extent, volume, and snow-on-sea ice volume for the northern (a-c) and southern (d-f) hemispheres may be compared for the standard resolution E3SMv2 and regionally-refined simulations. A 20-year industrial-era average (1979-1999) of the NOAA Sea Ice Climate Data Record (CDR) provides a rough benchmark of extent bias, also seen in Figure 4 below.

Arctic and North American regional refinement in E3SM provides a tractable solution to resolving coastal processes important for the United States with global climatic feedbacks. It also offers a mechanism to analyze scale dependency in polar model physics, and to understand the impact of better resolving dynamical processes including an eddy-permitting versus eddy-parameterized solution for the ocean, with better representation of atmospheric circulation features important in the Arctic. Our 500-year preindustrial simulations indicate that Arctic sea ice is thicker at the 99% compatibility interval with regional refinement for the entire annual cycle. Conversely, the null hypothesis is confirmed for all months of the year for the Southern Ocean, where both simulations exhibit statistically similar sea ice volume and resolve the Southern Hemisphere with the same resolution (Figure 3). Summer Arctic extent bias is greatly reduced with resolution, but winter extent bias is unaffected by the change.

Figure 4 (right): Comparison of Northern Hemisphere mean sea ice thickness and extent for March (a-b) and September (c-d) for 500-year preindustrial simulations at standard resolution and with regional refinement. Blue contours indicate model extent, orange provides an 20th-century (1979-1999) gauge of extent from the NOAA CDR also summarized in Figure 3. Regional refinement results in thicker Arctic Ocean sea ice, and removes a summer negative extent bias. The E3SMv2 winter sea ice bias remains intact regardless of mesh refinement. There is no significant difference in Southern Ocean sea ice thickness patterns between the two cases and where there is no regional refinement, and no significant difference in total Southern Ocean sea ice volume (see Figure 3).



Impact of Regional Refinement on Sea Ice Drift

Increased resolution results in increased autumnal and winter sea ice drift speeds, consistent with results from global high-resolution simulations in E3SM (Caldwell et al. 2019; https://doi.org/10.1029/2019MS001870). This is a consequence of several drivers including refined coastal currents, storm activity, and also eddies in the refined oceanic region.

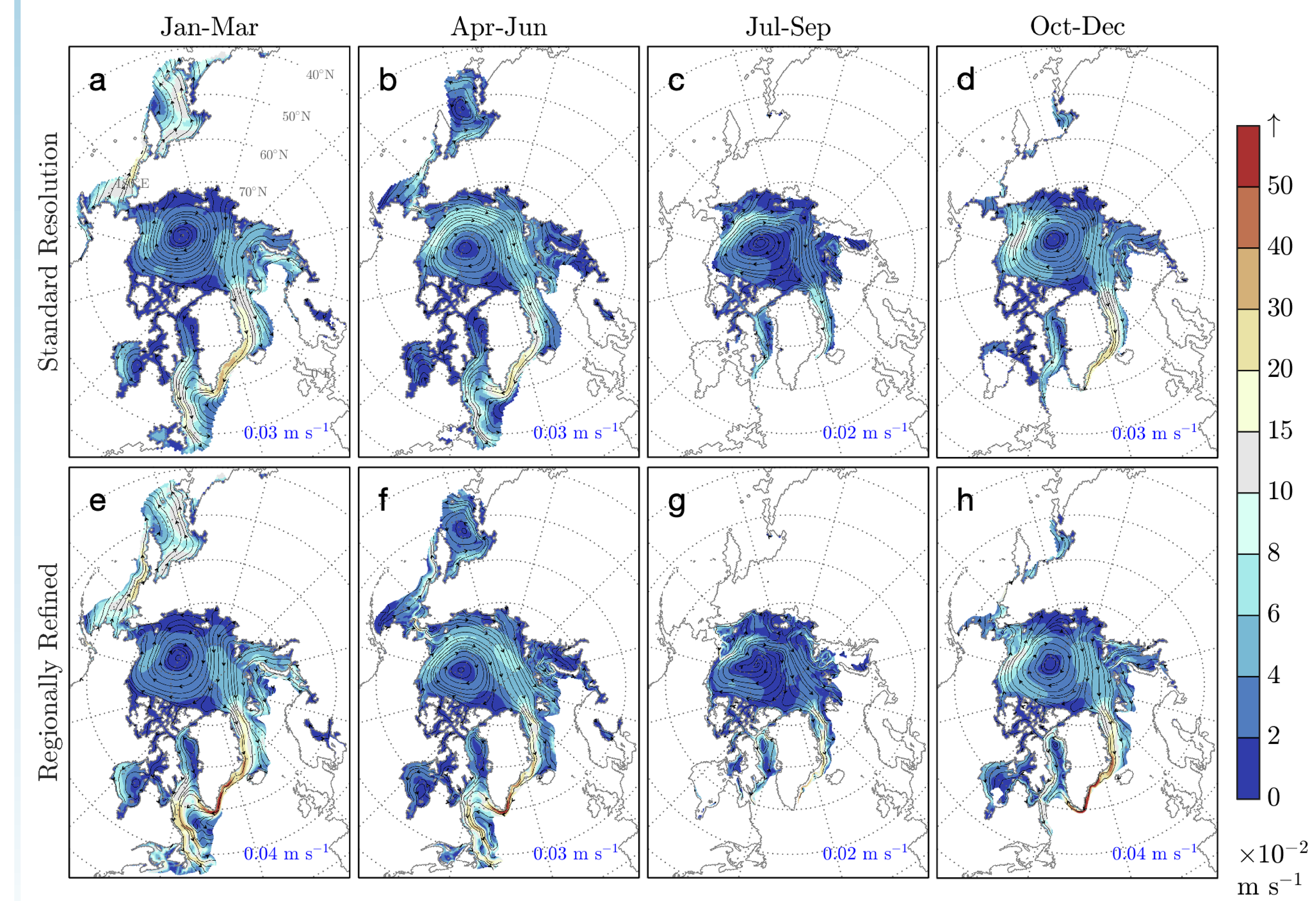


Figure 5 (above): 500-year preindustrial seasonally-averaged Northern Hemisphere sea ice drift at standard (a-d) and regionally-refined (e-h) resolution. The median drift speed across the field is given in blue in the lower right corner of each frame.

Affordable Computational Cost

The computational cost of the standard resolution model on the U.S. Department of Energy computer Chrysalis (AMD machine, 512 nodes, 64 cores per node) is roughly 3115 core hours per simulated year using 6784 cores with a throughput of 26.13 simulated years per day. This compares to the regionally-refined cost of around 12539 core hours per simulated year using 12800 cores, with a throughput of 12.25 simulated years per day: four times the cost at about 46% of the throughput of standard resolution.

	Nominal Resolution	Number of Columns
Ocean		
Standard Resolution	30–60 km	236,853
Arctic and North American RRM	14–60 km	407,420
Atmosphere		
Standard Resolution	110 km	21,600
North American RRM	25–110 km	57,816

Table 1 (above): Component model meshes used for simulations presented in this poster, where RRM abbreviates *Regionally Refined Mesh*. Standard resolution is the E3SM default, and the regionally refined simulation in this poster uses the Arctic and North American ocean RRM coupled to the North American atmosphere RRM. The ocean mesh is also used by the sea ice model, and the atmospheric mesh applies to land physics and biogeochemistry. The number of columns indicates the orthographic count of grid points on which scalars such as temperature, atmospheric humidity, ocean salinity, or sea ice thickness are calculated.

Conclusion and Next Steps

Increased Arctic resolution in E3SMv2 results in greatly increased sea ice volume along the Siberian and Canadian coasts. This result may be a reflection of limitations of ocean eddy-parameterization among other physics constraints, and we are now working to pinpoint the largest changes in mass and energy fluxes in the sea ice component to understand which aspect of regional Arctic refinement is most consequential.

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